Temperature Dependent Mechanical Properties of Materials: A Study Using Micromechanical Oscillators

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Motivation—Micromechanical oscillators have been developed for an increasing number of applications, including miniaturized acoustic, chemical or biological sensors (e.g., for Homeland Security), clocks and filters for high frequency electrical circuits, and resonant detectors of small force for scanning probe microscopy. For many of these applications, the critical signal to be measured is the absolute resonant frequency or a change in the resonant frequency of the oscillator. One confounding issue is that the resonant frequency of an oscillator changes with changing temperature due to the temperature dependence of the mechanical properties of the material. This work describes the development of an experimental capability to measure the temperature dependence of the full elastic properties of a thin film material through the use of flexural and torsional micromechanical oscillators.

Accomplishment—Flexural and torsional micromechanical oscillators were fabricated out of tetrahedral amorphous carbon, ta-C, which is one material that has been used in a variety of micromechanical oscillator applications. The flexural oscillators were comprised of cantilevers of varying lengths, from 10s to 100s of microns. The torsional oscillators were fabricated as paddle oscillators with beam widths of 0.5 microns and lengths of 10s of microns (see Fig. 1). E-beam lithography and surface micromachining processes were used to create the structures. These micromechanical oscillators were then mounted onto a resistive heater element bonded to a piezoelectric actuator with the entire system being inside a vacuum system. Light interferometry was used to measure oscillator resonant frequencies. Measurements of the oscillator properties were made over the temperature range from 300 K to 873 K. The Young's modulus, E, and shear modulus, G, were evaluated at each temperature by fitting the data of oscillator frequency as a function of oscillator length and applying linear elastic beam theory. Ta-C is a completely amorphous material, so it behaves as a true isotropic solid with only two independent elastic constants. The Poisson's ratio, ν, is calculated using $\nu = 0.5(E/G)-1$. Similarly, the three elastic constants, C_{11}, C_{12}, and C_{44} may also be obtained from knowledge of E and G. With the elastic constants thus obtained, the temperature dependence may be expressed using 2nd order polynomial fits. Figure 2 shows the temperature dependent Young's and shear moduli of ta-C and the subsequent polynomial fits. In both cases, a decrease in modulus of about 3% was observed over the temperature range from 300 K to 873 K.

Significance—Knowledge of the temperature dependent mechanical properties of a micromechanical oscillator enables the complete prediction of the oscillator resonance frequency at any temperature. This information is critical in order to account for and adjust for temperature-induced drift of the oscillator frequency–an important correction for oscillators used as frequency sources/filters or for sensing applications. The approach described here to obtaining the temperature dependent properties of thin film micro-mechanical oscillator materials is quite generic, and currently studies are being extended to the characterization of amorphous silicon nitride and polycrystalline diamond oscillators.

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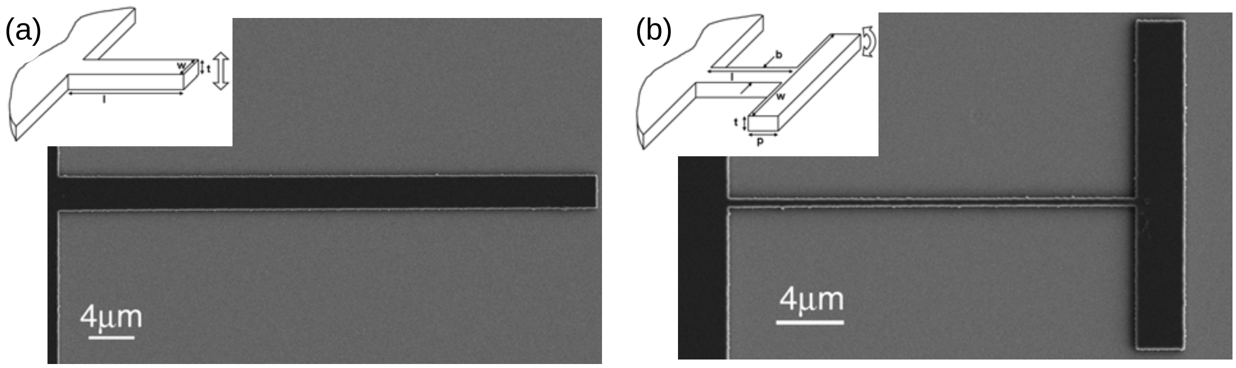

Figure 1. Schematic (insets) and SEM images of tetrahedral amorphous carbon (a) flexural oscillators and (b) torsional oscillators that were used in this study.

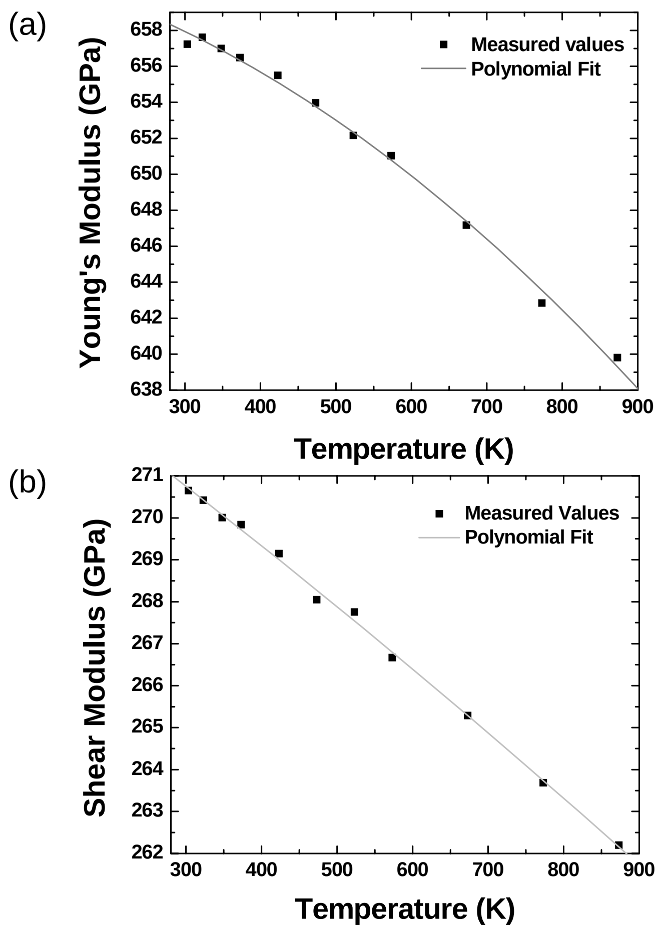

Figure 2. The measured temperature-dependent (a) Young's and (b) shear moduli of tetrahedral amorphous carbon. The solid lines are 2nd order polynomial fits to the data.